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A comprehensive analysis of conduction-controlled rewetting by the Heat Balance Integral Method

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Abstract

A two region conduction-controlled rewetting model of hot vertical surfaces with a constant wet side heat transfer coefficient and negligible heat transfer from dry side is solved by the Heat Balance Integral Method (HBIM). The HBIM yields a simple closed form solution for rewetting velocity and temperature distribution in both dry and wet regions for given Biot numbers. Using this method it has been possible to derive a unified relationship for one-dimensional object and two-dimensional slab and rod. The effect of convection is expressed by an effective Biot number whose exact value depends on the geometry and process parameters. The solutions are found to be exactly the same as reported by Duffey and Porthouse [R.B. Duffey, D.T.C Porthouse, The physics of rewetting in water reactor emergency core cooling, Nucl. Eng. Des. 25 (1973) 379–394], Thompson [T.S. Thompson, An analysis of the wet-side heat transfer coefficient during rewetting of a hot dry patch, Nucl. Eng. Des. 22 (1972) 212–224] and Sun et al. [K.H. Sun, G.E. Dix, C.L. Tien, Cooling of a very hot vertical surface by falling liquid film, ASME J. Heat Transfer 96 (1974) 126–131; K.H. Sun, G.E. Dix, C.L. Tien, Effect of precursory cooling on falling-film rewetting, ASME J. Heat Transfer 97 (1974) 360–365]. Good agreement with experimental results is also observed.

Keywords: Rewetting; Quenching; Integral method; Conduction controlled; Effective Biot number

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1. Introduction

Rewetting of hot surface is a process in which a liquid wets a hot surface by displacing its own vapour that otherwise prevents the contact between the solid and liquid phases. When a liquid comes in contact with a sufficiently hot surface a vapour blanket is formed that separates the liquid from the surface. As the surface cools, the vapour film collapses and the surface–liquid contact is re-established. The phenomenon of non-wetting of a hot surface by liquid and its subsequent wetting due to the collapse of the intermediate vapour film has been long observed under different contexts. This phenomenon is of practical importance in the controlled rewetting in nuclear reactors during emergency loss of coolant, cryogenic systems, metallurgical processes and space station thermal control. During a postulated "loss of coolant" accident, the hot core has to pass essentially through a rewetting phase. A delay in effective cooling may result in oxidation, ballooning and melting of the fuel element and other catastrophes. This has generated immense interest in studying rewetting through both theoretical simulation [1–6] and experimental observation [1,7–9].

Falling film rewetting for several vertical geometries such as plates [5,10], rods [11–13] and tubes [14] has been modeled by a number of researchers. In general, in all models, a moving rewetting front that divides the solid into two distinct region is considered. Most of the models also consider a constant rewetting velocity that reduces the problem into a quasi-static one.

Initial efforts were made to formulate one-dimensional conduction models [1,2] that are reasonably successful in correlating rewetting phenomena at low Peclet number. Tien and Yao [10] presented the asymptotic solutions of

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Nomenclature

A, B, D	constants defined in text
a	radius of cylinder, m
Bi	Biot number $\frac{h\delta}{K}$ and $\frac{ha}{K}$ in one-dimensional and two-dimensional case, respectively
C	specific heat, J/kg °C
HBIM	Heat Balance Integral Method
h	heat transfer coefficient, W/m^2 °C
K	thermal conductivity, W/m °C
M	effective Biot number
N	magnitude of precursory cooling
Pe	dimensionless wet front velocity $\frac{u\delta\rho C}{K}$ and $\frac{\rho Cua}{K}$ for one-dimensional and two-dimensional case, respectively
T	temperature, °C
T_{O}	wet front temperature that corresponds to the temperature at the minimum film boiling heat flux, °C
T_{S}	saturation temperature, °C
T_{W}	initial temperature of the dry surface, °C
t	time, s
u	wet front velocity, m/s
$\bar{x},\bar{y},\bar{r}$	length coordinates, m
x, y, r	dimensionless length coordinates

Greek symbols

α, β, γ	constants defined in text
δ	wall thickness, m
θ	non-dimensional temperature defined in Eq. (3)
θ_1	non-dimensional temperature parameter defined in Eq. (3)
$\bar{\theta}$	non-dimensional temperature integral defined in Eq. (7)
θ_i	non-dimensional surface temperature
ρ	density, kg/m^3

Subscripts

0	quench front
l	liquid side
v	dry side
+	evaluated at an infinitesimal increment of distance
−	evaluated at an infinitesimal increment of distance
1, 2, 3, 4	separation constants

a two-dimensional conduction model which clearly demonstrates the different physical pictures for the cases of high and low coolant flow rates and also establishes the limitation of one-dimensional model for high values of Peclet number and Biot number. A variety of techniques have been used for solving two-dimensional conduction models for falling film rewetting. Some of the important studies are elaborated below.

Because of mathematical difficulty, most two-dimensional analyses are either approximate or numerical ones. The solution by separation of variables to rewetting problem was first considered by Duffey and Porthouse [4]. They retained only the first term in the series solution. However, Coney [5] reported that using a small number of terms in a series yields inaccurate results due to slow convergence of the series. An approximate solution to the same model for a cylindrical rod was presented by Blair [11]. Tien and Yao [10] first applied the Wiener–Hopf technique to a two-dimensional rewetting problem of a rectangular slab, while an exact solution to the same problem was presented by Castiglia et al. [15], employing the method of separation of variables. Numerical solutions of conduction controlled rewetting were provided by Satapathy et al. [14,16], Thompson [17], and Raj and Date [18] by using the finite difference technique.

A solution to the rewetting problem was obtained by Olek [19] by considering rewetting as a conjugate heat transfer problem. In this method the heat transfer coefficient need not be specified unlike other rewetting models but it may be obtained as a part of the solution. Recently, a solution to the rewetting problem was obtained by Dorfman [20] by considering a transient rewetting process. It was observed that the transient cooling process is governed by a dimensionless parameter called the Leidenfrost number, expressed as the ratio of Biot number to square of Peclet number.

HBIM is one of many semi-analytical methods used to solve conduction problems [21–23]. This is analogous to classical integral technique used for fluid flow and convective heat transfer analysis [24]. This technique is simple yet it gives reasonable accuracy. HBIM has mostly been employed for a variety of Stefan problems involving one-dimensional conduction problems. However, efforts have also been made to employ HBIM for two-dimensional problems [23]. Sfeir [25] and Burmeister [26] has successfully employed this technique for analysis of two-dimensional fins. Recently some modifications [27,28] have been suggested to the basic HBIM. Rewetting of hot solid exhibits some similarity with the classical Stefan problem. Both are moving boundary problems and in both the cases the solution space can be divided into two domains with a strong temperature gradient at the interface. However only a single investigation [29] has yet been reported on the application of HBIM for rewetting analysis. This has motivated application of HBIM for a comprehensive study of conduction controlled rewetting. In the present investigation three different cases of rewetting have been considered. A generalization of all three cases is possible by application